

NEUTRALINO DARK MATTER

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Abstract

We examine the main properties of relic neutralinos in the context of the Minimal Supersymmetric extension of the Standard Model. We present a whole set of results obtained for the relic abundance and for detection rates with a model constrained according to the latest accelerator data. Predicted detection rates for relic neutralinos are compared to the present experimental bounds. A comparison with results obtained with more sophisticated theoretical schemes with unification assumptions at M_{GUT} is presented too. We also briefly discuss some properties of a Higgsino-like neutralino which has recently been suggested in connection with a supersymmetric interpretation of a single event at the Fermilab Tevatron.

1 Introduction

The neutralino is currently being considered as a favourite candidate for Cold Dark Matter (CDM). In fact, the neutralino turns out to be the Lightest Supersymmetric Particle (LSP) in extended regions of the supersymmetric parameter space and then, if protected by R-parity conservation (that we assume to hold), it would have decoupled from the primeval plasma and would be present in the Universe as a fossil particle.

The properties of the neutralino vary quite noticeably as one moves in the supersymmetric parameter space: from some regions where the neutralino relic abundance $\Omega_\chi h^2$ (h is the present Hubble expansion rate in units of $100 \text{ Km} \cdot$

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$\text{s}^{-1} \cdot \text{Mpc}^{-1}$) turns out to be large (and detection rates low) to other regions where the other extreme situation of a negligible Ω_χ (and of sizable detection rates) occurs. It is remarkable that there are domains of the supersymmetric parameter space, where the neutralino can provide a relic abundance in the preferred density range for CDM¹

$$\Omega_{CDM}h^2 = 0.2 \pm 0.1. \quad (1)$$

However, even in the case when the neutralino does not contribute significantly to the average density of the Universe, experimental searches for relic neutralinos would be of the utmost interest for a number of cosmological and particle-physics aspects.

In this paper we examine the main properties of relic neutralinos in the context of the Minimal Supersymmetric extension of the Standard Model (MSSM)². Indeed, this scheme provides a most convenient phenomenological framework at the electroweak scale (M_Z), without assuming too strong, arbitrary theoretical hypotheses. After a short presentation of the theoretical scheme, we report the main results concerning neutralino relic abundance and predicted detection rates. A comparison with results obtained with more sophisticated theoretical schemes is presented too.

Furthermore, we also briefly discuss some properties of a Higgsino-like neutralino which has recently been suggested in connection with a supersymmetric interpretation of a single event at the Fermilab Tevatron.

2 The Minimal Supersymmetric Standard Model

The MSSM is based on the same gauge group as the Standard Model and contains the supersymmetric extension of its particle content. The Higgs sector is modified as compared to that of the Standard Model, because it requires two Higgs doublets H_1 and H_2 in order to give mass both to down- and up-type quarks and to cancel anomalies. After Electro-Weak Symmetry Breaking (EWSB), the physical Higgs fields consist of two charged particles and three neutral ones: two scalar fields (h and H) and one pseudoscalar (A). The Higgs sector is specified at the tree level by two independent parameters: the

mass of one of the physical Higgs fields (we will use the mass m_A of the A boson) and the ratio of the two vacuum expectation values, usually defined as $\tan \beta = v_2/v_1 \equiv \langle H_2 \rangle / \langle H_1 \rangle$.

Apart from the Yang-Mills Lagrangian, other characteristic elements of the model are the superpotential, which contains all the Yukawa interactions and the Higgs-mixing term $\mu H_1 H_2$, and the soft-breaking Lagrangian, which models the breaking of supersymmetry

$$\begin{aligned}
-\mathcal{L}_{soft} = & \sum_i m_i^2 |\phi_i|^2 + \left\{ \left[A_{ab}^l h_{ab}^l \tilde{L}_a H_1 \tilde{R}_b + A_{ab}^d h_{ab}^d \tilde{Q}_a H_1 \tilde{D}_b \right. \right. \\
& + \left. \left. A_{ab}^u h_{ab}^u \tilde{Q}_a H_2 \tilde{U}_b + \text{h.c.} \right] - B\mu H_1 H_2 + \text{h.c.} \right\} \\
& + \sum_i M_i (\lambda_i \lambda_i + \bar{\lambda}_i \bar{\lambda}_i). \tag{2}
\end{aligned}$$

Here the notations are the following: the ϕ_i are the scalar fields, the λ_i are the gaugino fields, \tilde{Q} and \tilde{L} are the doublet squark and slepton fields, respectively, and \tilde{U} , \tilde{D} and \tilde{R} denote the $SU(2)$ -singlet fields for the up-squarks, down-squarks and sleptons, m_i and M_i are the mass parameters of the scalar and gaugino fields, respectively. A denotes the trilinear and B the bilinear supersymmetry breaking parameters. The Yukawa interactions are described by the parameters h , which are related to the masses of the standard fermions by the usual expressions, *e.g.*, $m_t = h^t v_2$.

The tree-level scalar potential for the neutral Higgs fields turns out to be

$$V_0 = (M_{H_1}^2 + \mu^2) |H_1|^2 + (M_{H_2}^2 + \mu^2) |H_2|^2 - B\mu (H_1 H_2 + \text{h.c.}) + \text{quartic D terms.} \tag{3}$$

When the electro-weak symmetry breaking is triggered by H_1 and H_2 acquiring vacuum expectation values v_1, v_2 with the condition $v_1^2 + v_2^2 \equiv v^2 = 2m_W^2/g^2$, the potential V_0 takes the standard form of a Higgs potential, provided the following constraints are satisfied:

$$\sin 2\beta = \frac{-2B\mu}{M_{H_1}^2 + M_{H_2}^2 + 2\mu^2} \tag{4}$$

$$M_Z^2 = 2 \frac{M_{H_1}^2 - M_{H_2}^2 \tan^2 \beta}{\tan^2 \beta - 1} - 2\mu^2. \tag{5}$$

Notice that the sign of μ is defined according to the convention of Refs. ². We remark that Eqs.(3–5) are expressed at the tree level. However, in the calculations that we will report later, 1-loop corrections to V_0 are included ³.

As is manifest from the previous formulae, the theoretical model contains an exceedingly large number of parameters. In order to have a viable phenomenological model we reduce the number of free parameters by introducing the following usual assumptions:

- $A_{33}^u = A_{33}^d = A_{33}^l \equiv A$; all other A_{ab} 's are set to zero
- all squarks are taken as degenerate: $m_{\tilde{q}_i} \equiv m_0$, except for $m_{\tilde{t}}$
- all sleptons are taken as degenerate with $m_{\tilde{l}_i} \equiv m_0$
- the gaugino masses are assumed to be renormalised as the gauge couplings,
 $M_1 : M_2 : M_3 = \alpha_1 : \alpha_2 : \alpha_3$; thus in particular $M_1 = (5/3) \tan^2 \theta_W M_2$.

We emphasize that all these relations are meant to be taken at the M_Z scale.

It is worth noticing that any variation in some of these assumptions, if required, can be introduced straightforwardly without implying any other modification in the general scheme. The flexibility of this phenomenological approach is not shared by other more theoretically-constrained models.

In force of the conditions previously discussed, the number of independent parameters is reduced to seven. We choose them to be: $M_2, \mu, \tan \beta, m_A, m_0, m_{\tilde{t}}, A$. In terms of these parameters, the supersymmetric space is further constrained by the following requirements:

- all experimental bounds on Higgs, neutralino, chargino and sfermion masses are satisfied (taking into account also the new data from LEP2⁴)
- the neutralino is the Lightest Supersymmetric Particle (LSP) (i.e., regions where gluino or squarks or sleptons are LSP are excluded)
- constraints due to the $b \rightarrow s + \gamma$ process are taken into account⁵

- the neutralino relic abundance does not exceed the cosmological bound, i.e. $\Omega_\chi h^2 \leq 1$.

As usual, any neutralino mass-eigenstate is written as a linear superposition

$$\chi_i = a_i \tilde{\gamma} + b_i \tilde{Z} + c_i \tilde{H}_s + d_i \tilde{H}_a \quad (6)$$

where $\tilde{\gamma}, \tilde{Z}$ are the photino and zino states and \tilde{H}_s, \tilde{H}_a are defined by $\tilde{H}_s = \sin\beta \tilde{H}_1^\circ + \cos\beta \tilde{H}_2^\circ$, $\tilde{H}_a = \cos\beta \tilde{H}_1^\circ - \sin\beta \tilde{H}_2^\circ$, in terms of the higgsino fields $\tilde{H}_1^\circ, \tilde{H}_2^\circ$, supersymmetric partners of the Higgs fields H_1°, H_2° . In the following we will simply call neutralino the eigenstate of lowest-mass and use $\chi \equiv \chi_1$. Fig.1 gives the isomass contours in the $\mu - M_2$ plane.

In the same plot, the region excluded by the LEP data and the contour lines for the composition parameter $P \equiv a_1^2 + b_1^2$ are also displayed.

Various properties of relic neutralinos in the MSSM have been considered by a number of authors. Some of the most recent ones are given in Refs.^{6,7}. In this review, we present a whole set of results concerning the main properties for relic neutralinos (relic abundance and detection rates) performed in the same consistent theoretical framework⁸. The techniques employed for the calculation of these various quantities are those presented in Refs.^{9,10,11}. The experimental constraints have been updated to include the latest LEP2 data⁴. Only the predictions for the \bar{p}/p ratio are not given here, since they are presented and discussed in an accompanying paper in these Proceedings¹². Our results for the neutralino relic abundance and detection rates are provided in the form of scatter plots. The independent parameters of the model have been varied in the following ranges:

$$\begin{array}{lll} 10 \text{ GeV} & \leq M_2 & \leq 500 \text{ GeV} \\ 10 \text{ GeV} & \leq \mu & \leq 500 \text{ GeV} \\ 50 \text{ GeV} & \leq m_A & \leq 500 \text{ GeV} \\ 100 \text{ GeV} & \leq m_0 & \leq 500 \text{ GeV} \\ 100 \text{ GeV} & \leq m_{\tilde{t}} & \leq 500 \text{ GeV} \end{array}$$

$$\begin{aligned}
-3 &\leq A \leq +3 \\
1.1 &\leq \tan\beta \leq 55
\end{aligned}
\tag{7}$$

Let us mention here that in more sophisticated supersymmetric models the properties at the M_Z scale are derived from properties at the Gran Unification scale M_{GUT} by employing the renormalization group equations. One of the nicest features of this approach is the link between the supersymmetry breaking and the EWSB, which is induced radiatively. These supersymmetric schemes are usually based on assumptions of unification at M_{GUT} , not only for the gauge coupling constants, but also for Yukawa couplings and for the soft-breaking parameters (scalar masses, gaugino masses, trilinear couplings). These assumptions have very strong consequences for the neutralino phenomenology at the M_Z scale. Relaxation of the universality assumptions, for instance the one concerning the scalar masses^{13,14}, may substantially modify the main properties of relic neutralinos^{1,15}. We do not discuss these more refined supersymmetric models in this paper; only at the end of the next section we will compare some results obtained in the MSSM with the ones obtainable in theoretical schemes with and without universality conditions on the soft scalar masses¹⁶.

3 Relic abundance and detection rates in MSSM

Now we present our main results. Fig.2 shows the neutralino relic abundance $\Omega_\chi h^2$ as a function of m_χ in the form of a scatter plot obtained by varying the parameters over the ranges of Eq.(7); $\Omega_\chi h^2$ has been calculated with the method illustrated in Ref.⁹.

The configurations giving an $\Omega_\chi h^2$ in conflict with the cosmological bound have already been removed. As expected, large values of the relic abundance are provided by configurations with small $\tan\beta$ and large m_A , since under these circumstances the neutralino pair-annihilation cross section is small. For the same reason large $\tan\beta$ and small m_A entail small values of $\Omega_\chi h^2$. By way of example, in Fig.2 two contour lines denote the values of $\Omega_\chi h^2$ for two subsets of neutralino configurations for extreme values of $\tan\beta$ and m_A .

We turn now to the presentation of detection rates for two classes of searches for relic neutralinos:

- Direct detection, i.e. measurement of the energy released by a neutralino in its scattering off a nucleus in an appropriate detector, by using very different experimental techniques⁶. Some of the most recent experimental results are given in Refs.^{17,18,19,20,21,22}. The rates for direct detection are calculated here as explained in Ref.¹⁰.
- Detection of the possible signals consisting of up-going muons through a neutrino telescope generated by neutrinos produced by pair annihilations of neutralinos captured and accumulated inside the Earth and the Sun. The evaluation of the muon fluxes, which is a rather elaborate multistep process, has been performed here according to the procedure described in Ref.¹¹, to which we refer for details of the calculations and for references.

For a presentation of the results concerning a possible excess in the \bar{p}/p ratio in the cosmic rays we refer to Ref.¹².

We remind that the detection rates for both direct detection and detection of the up-going muon fluxes are proportional to the neutralino local (solar neighborhood) density ρ_χ . To assign a value to this quantity we employ here the following rescaling recipe²³. For each point of the parameter space, we take into account the relevant value of the cosmological neutralino relic density. When $\Omega_\chi h^2$ is larger than a minimal $(\Omega h^2)_{min}$, compatible with observational data and with large-scale structure calculations, we simply put $\rho_\chi = \rho_l$. When $\Omega_\chi h^2$ turns out to be less than $(\Omega h^2)_{min}$, and then the neutralino may only provide a fractional contribution $\Omega_\chi h^2 / (\Omega h^2)_{min} \equiv \xi$ to Ωh^2 , we take $\rho_\chi = \rho_l \xi$. The value to be assigned to $(\Omega h^2)_{min}$ is somewhat arbitrary, in the range $0.03 \lesssim (\Omega h^2)_{min} \lesssim 0.3$. In the present paper we have used $(\Omega h^2)_{min} = 0.03$. As far as the value of ρ_l is concerned, we have taken the representative value $\rho_l = 0.5 \text{ GeV} \cdot \text{cm}^{-3}$. This corresponds to the central value of a recent determination of ρ_l , based on a flattened dark matter distribution and microlensing data²⁴: $\rho_l = 0.51^{+0.21}_{-0.17} \text{ GeV} \cdot \text{cm}^{-3}$.

Fig.3 shows a comparison between one of the most stringent experimental upper bounds: $R_{Ge}^{expt}(6 \text{ KeV} \leq E_{ee} \leq 8 \text{ KeV}) = 1.2 \text{ counts}/(\text{Kg day})$ (this is extracted from the experimental data of Ref.²¹) and the predicted values for the same quantity.

These results are also reported in Fig.4 in a plot versus $\Omega_\chi h^2$, to show the expected correlation between the signal and the relic abundance.

Table 1: Values of the astrophysical and cosmological parameters relevant to direct detection rates. $V_{r.m.s.}$ denotes the root mean square velocity of the neutralino Maxwellian velocity distribution in the halo; V_{esc} is the neutralino escape velocity and V_{\odot} is the velocity of the Sun around the galactic centre; ρ_{loc} denotes the local dark matter density and $(\Omega h^2)_{min}$ the minimal value of Ωh^2 . The values of set I are the median values of the various parameters, the values of set II are the extreme values of the parameters which, within the physical ranges, provide the lowest estimates of the direct rates (once the supersymmetric parameters are fixed).

	Set I	Set II
$V_{r.m.s.}(\text{km} \cdot \text{s}^{-1})$	270	245
$V_{esc}(\text{km} \cdot \text{s}^{-1})$	650	450
$V_{\odot}(\text{km} \cdot \text{s}^{-1})$	232	212
$\rho_{loc}(\text{GeV} \cdot \text{cm}^{-3})$	0.5	0.2
$(\Omega h^2)_{min}$	0.03	0.3

In Fig.3 we notice that for some configurations, with large $\tan \beta$ and small m_A , the predicted rates are above the experimental limit. However, we emphasize that this feature cannot be used to exclude these neutralino configurations, since one has to take into account the large uncertainties affecting some of the astrophysical (and cosmological) quantities which enter in the evaluation of the detection rates. Table 1 reports two sets of values for the relevant quantities of this kind. Set I corresponds essentially to the central values for the various parameters, whereas set II corresponds to those values of the parameters, which, within the relevant allowed ranges, provide the lowest detection rates (once the supersymmetric variables are fixed).

For all the results of the present review, unless specified differently, the set I has been employed. This is, for instance, the case for the detection rates reported in Fig.3. Now it turns out that, if the calculation of the rate R_{Ge}^{expt} ($6 \text{ KeV} \leq E_{ee} \leq 8 \text{ KeV}$) is performed using set II, all predicted rates are below the experimental upper bound. However, it has to be stressed that the maximum value of the rate falls short of the limit only by a factor of 2. This obviously implies that even a moderate improvement in experimental sensitivities in direct searches may provide an essential information about the neutralino parameter space.

A more direct illustration of this point is provided by an inspection of the neutralino-nucleon cross section. Fig.5 gives a comparison of the predicted values for $\xi \cdot \sigma_{scalar}^{(n)}$ with the relevant upper bound (as derived from the current

experimental data Refs.^{17,18,19,20,21}).

$\sigma_{scalar}^{(n)}$ stands for the neutralino-nucleon scalar cross-section, responsible for coherent effects in processes involving nuclei. Here set I has been used. The results of the same calculation with set II for the astrophysical and cosmological parameters are shown in Fig.6. We notice that no predicted values are above the experimental upper bound; however, some neutralino configurations are close to it. We do not consider here explicit upper bounds on the spin-dependent neutralino-nucleon cross section as obtainable from present experimental data. This point will be discussed in detail in a forthcoming paper ²⁵.

Let us turn now to the indirect measurements, based on the outcome of high-energy neutrinos from neutralino pair annihilation in celestial bodies. Here we limit ourselves to the emission from the center of the Earth. The flux of the ensuing up-going muons, integrated over muon energies above 1 GeV and over a cone of half aperture of 30° centered at the nadir, is shown in Fig.7. The horizontal line denotes the Baksan upper limit: $\Phi_\mu^{Earth} \leq 2.1 \times 10^{-14} \text{cm}^{-2}\text{s}^{-1}(90\%C.L.)$ ²⁶.

Also in this case, many configurations provide fluxes in excess of the experimental limit. However, if set II of Table 1 is employed, then the number of neutralino configurations staying above the experimental bound turns out to be marginal. It then follows that present data from neutrino telescopes are not yet capable of excluding physical regions of the supersymmetric parameter space (contrary to the conclusions of Ref.²⁶).

Fig.8 displays Φ_μ^{Earth} versus R_{Ge} to show the expected correlation between these two quantities. Also displayed are the locations of configurations which would be selected by a model with universality assumptions at M_{GUT} and by one where the unification condition on soft scalar masses has been somewhat relaxed ¹. This illustrates how strong are the constraints imposed by strict universality conditions at M_{GUT} and how sensitive are the signals to these assumptions.

From what we have discussed in this part, we can conclude that the present sensitivities for the experimental searches examined above are not yet in the position of constraining the supersymmetric model. However, the foreseeable improvements in these sensitivities will make soon possible an exploration of

some regions of the neutralino parameter space.

4 A Higgsino-like relic neutralino

It has recently been conjectured²⁷ that the CDF event $p\bar{p} \rightarrow e^+e^-\gamma\gamma E_T$ ²⁸ is due to a decay chain involving two neutralino states (the lightest and the next-to-lightest ones). The lightest neutralino (that we denote as χ_{AKM}) has been further considered in Ref.²⁹ as a candidate for cold dark matter. If the neutralino interpretation of Ref.²⁷ is correct, then the neutralino would be confined in a rather narrow region of the supersymmetric parameter space, at least as far as some parameters (such as $M_2, \mu, \tan\beta$) are concerned. An important question is whether or not a relic χ_{AKM} could be detected either directly or indirectly. Here we only report a few results of a thorough investigation carried out in Ref.³⁰, to which we refer for further details (some detection signals for χ_{AKM} have also been investigated in Refs.^{29,31} for a limited domain of the χ_{AKM} parameter space and under the hypothesis that χ_{AKM} provides a large contribution to Ω).

In Ref.³⁰ it is shown that for most regions of the parameter space the detectability of a relic χ_{AKM} would require quite substantial improvements in current experimental sensitivities. Some favorable perspectives for investigating a region of the χ_{AKM} parameter space, around the maximal $\tan\beta$ value allowed by the model of Ref.²⁷ (*i.e.*, $\tan\beta \simeq 2.5$), are offered by measurements of neutrino fluxes from the center of the Earth and of an excess of \bar{p}/p in cosmic rays. To illustrate this point we display in Fig.9 \bar{p}/p versus Φ_μ^{Earth} for χ_{AKM} configurations with $1.5 \leq \tan\beta \leq 2.5$.

Diamonds and crosses denote the values of the signals when these are within two orders of magnitude from the current value of at least one of the relevant experimental upper bounds (at 90 % C.L.). Diamonds (crosses) denote values obtained by evaluating the neutralino relic abundance with the exact expression (with a low-velocity approximation). Dots denote the values of the signals for the other configurations, calculated in the low-velocity approximation only. The experimental bounds are displayed by the horizontal and the vertical lines: $\bar{p}/p \leq 7.5 \times 10^{-5}$ ³², $\Phi_\mu^{Earth} \leq 2.1 \times 10^{-14} \text{ cm}^{-2} \text{ s}^{-1} (90\% \text{ C.L.})$ ²⁶.

Let us finally remark that the conjecture of Ref.²⁷ is certainly very intriguing; if correct, it would have important consequences in particle physics

and possibly also in cosmology. However, great caution is in order, because of the existence of only a single event of the type $p\bar{p} \rightarrow e^+e^-\gamma\gamma E_T$ and of the non-uniqueness in its interpretation^{27,33,34,35,36,37}.

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Figure 1: Isomass and isocomposition contour lines for the neutralino in the $\mu - M_2$ plane for $\tan \beta = 10$. The region excluded by LEP is denoted by dots. m_χ is in units of GeV.

Figure 2: Neutralino relic abundance as a function of the neutralino mass. The solid (dashed) line delimits the region where neutralino configurations with $\tan\beta = 55$ and $m_A = 50\text{-}60$ GeV (with $\tan\beta = 1.1$ and $m_A = 500$ GeV) are located.

Figure 3: R_{Ge} (as defined in the text) versus m_χ . The contour lines have the same meaning as in Fig.2.

Figure 4: R_{Ge} versus the relic abundance.

Figure 5: The neutralino-nucleon scalar cross section multiplied by the scaling factor ξ versus m_χ . Set I of Table 1 is used. The contour lines have the same meaning as in Fig.2.

Figure 6: Same as in Fig.5, except that here set II of Table 1 is used.

Figure 7: Φ_{μ}^{Earth} versus m_{χ} . The contour lines have the same meaning as in Fig.2.

Figure 8: Φ_{μ}^{Earth} versus R_{Ge} . The solid line delimits the location of configurations for the MSSM considered in this paper. The diamonds (the dots) denote the values for a model with strict universality assumptions at M_{GUT} (with a deviation from unification condition on the soft scalar masses).

Figure 9: \bar{p}/p versus Φ_μ^{Earth} for χ_{AKM} configurations. The meaning of the symbols is explained in the text.